The impact of intensive groundwater abstraction on recharge to a shallow regional aquifer system: evidence from Bangladesh

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Abstract Quantitative evaluations of the impact of groundwater abstraction on recharge are rare. Over a period (1975–2007) during which groundwater abstraction increased dramatically in the Bengal Basin, changes in net groundwater recharge in Bangladesh are assessed using the water-table fluctuation method. Mean annual groundwater recharge is shown to be higher (300–600mm) in northwestern and southwestern areas of Bangladesh than in southeastern and northeastern regions (<100mm) where rainfall and potential recharge are greater. Net recharge in many parts of Bangladesh has increased substantially (5–15mm/year between 1985 and 2007) in response to increased groundwater abstraction for irrigation and urban water supplies. In contrast, net recharge has slightly decreased (−0.5 to −1mm/year) in areas where groundwater-fed irrigation is low (<30% of total irrigation) and where abstraction has either decreased or remained unchanged over the period of 1985–2007. The spatio-temporal dynamics of recharge in Bangladesh illustrate the fundamental flaw in definitions of "safe yield" based on recharge estimated under static (non-pumping) conditions and reveal the areas where (1) further groundwater abstraction may increase actual recharge to the shallow aquifer, and (2) current groundwater abstraction for irrigation and urban water supplies is unsustainable.

Keywords Groundwater recharge/water budget · Groundwater monitoring · Agriculture · Over-abstraction · Bangladesh

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Introduction

Groundwater recharge is influenced not only by climate variability but also human intervention including, most substantially, groundwater abstraction. Globally, irrigation is responsible for more than 65% of all freshwater withdrawals. At present, one quarter of the world's irrigated land is supplied by groundwater and 75% of these lands are located in Asia (Shah et al. 2007). Groundwater-fed irrigation is conducted to cultivate high-yielding rice during the dry season in South Asia where India and Bangladesh represent the world's second and fourth biggest rice-producing nations respectively (Scott and Sharma 2009; IRRI 2010). Over the last 50 years, groundwater abstraction on the Indian subcontinent increased from about 10–20 km^3/year to approximately 260 km^3/year (Shah et al. 2003; Giordano 2009). Current abstraction exceeds potential groundwater recharge to the Ganges-Brahmaputra and Indus basins and is estimated to be ~246 km^3/year (CGWB 2006). In Bangladesh, total annual (2004–2005) irrigation water use is estimated to be ~24 km^3 of which 18 km^3 comes from groundwater (Siebert et al. 2010) via a range of pumping technologies (Fig. 1). Recent studies in India and Bangladesh (Rodell et al. 2009; Shamsudduha et al. 2009a; Tiwari et al. 2009) report declining trends in groundwater levels (0.1–0.5 m/year) which indicate reductions in aquifer storage from unsustainable groundwater abstraction for both irrigation and urban water supplies.

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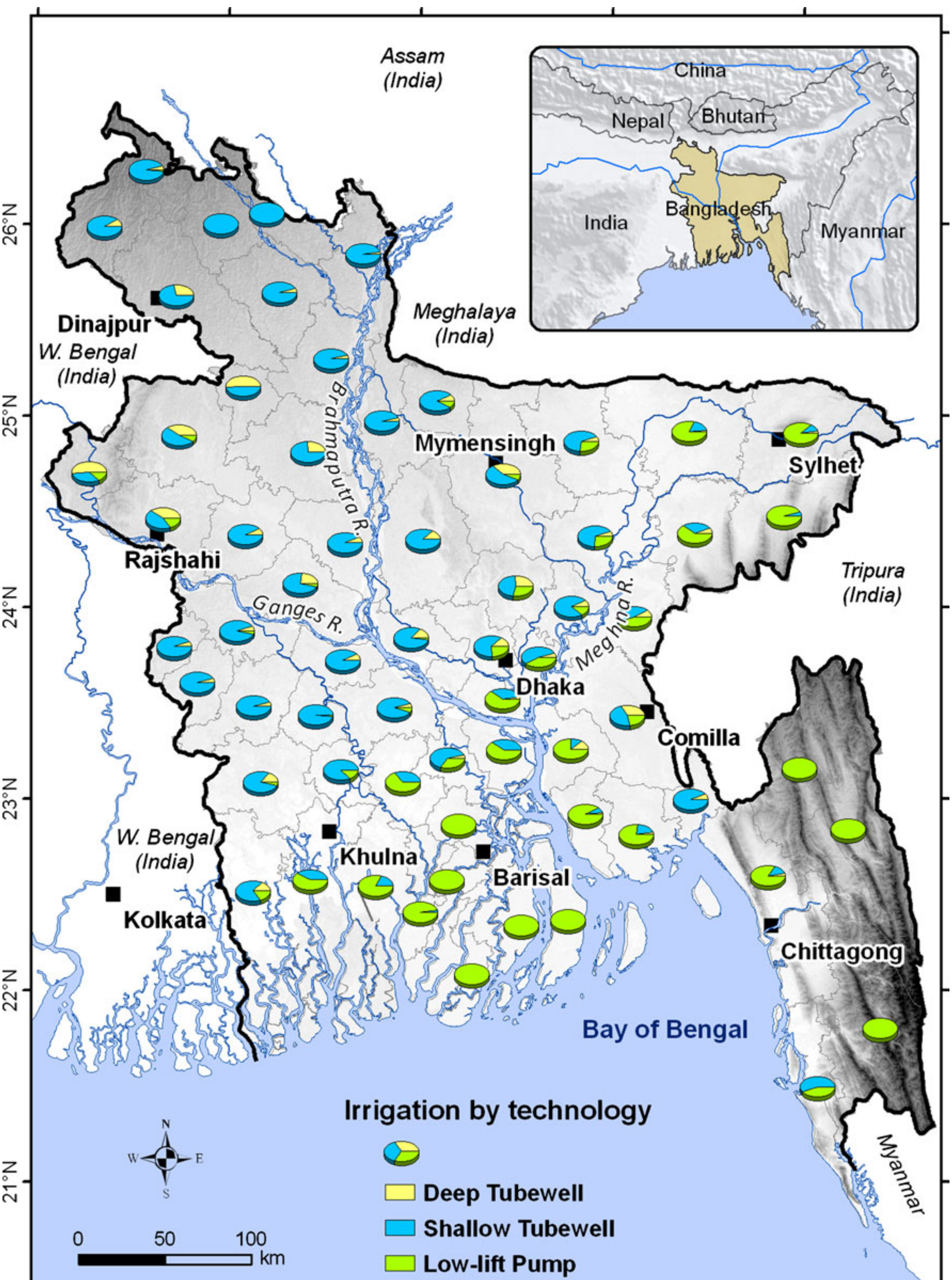

Fig. 1 Relative proportion (percentage) of dry-season irrigation in 2006 by various pumping technologies in 64 districts in Bangladesh. Locations of major district towns are given

The regional-scale impacts of intensive groundwater abstraction on recharge have rarely been subject to direct examination yet are central to the arguments of several authors (e.g. Sophocleous 2000; Alley et al. 2002; Alley and Leake 2004) who challenge the concept of 'safe yield' defined by the long-term balance between annual groundwater abstraction and recharge under natural (non-pumping) conditions advocated by others (e.g., Döll and Fiedler 2008;

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Kundzewicz and Döll 2009; Döll 2009). In the Bengal Basin, several localized studies of the mobilization of arsenic in shallow groundwater (Harvey et al. 2006; Klump et al. 2006; Stute et al. 2007; Neumann et al. 2009) have speculated about a regional-scale perturbation of the shallow groundwater system caused by widespread pumping for irrigation. Abstraction, it is asserted, could induce groundwater recharge by either capturing surface water from rivers (Bredehoeft 2002) or increasing available aquifer storage through the dry season thereby enhancing recharge during the subsequent wet (monsoon) season (MPO 1987). Recent, regional groundwater flow modeling in the Bengal Basin (Michael and Voss 2009) provides support for this hypothesis. Here, the spatio-temporal impacts of intensive groundwater abstraction on recharge to the shallow, alluvial aquifer system of Bangladesh is directly assessed using a recently compiled national database of water-level fluctuations and distributed estimates of specific yield. The study seeks to estimate actual (net) groundwater recharge to the shallow regional aquifer system for the period of 1975–2007, and to compare net groundwater recharge prior to the widespread adoption of groundwater-fed irrigation (1975–1980) with net groundwater recharge in a more recent period (2002–2007).

Surface geology, soil, and hydrogeology of Bangladesh

Bangladesh occupies much of the Bengal Basin, one of the largest sedimentary basins in the world and the major depocenter of sedimentary fluxes from the Himalayan and Indo-Burman mountain ranges which are drained by the Ganges-Brahmaputra-Meghna (GBM) river system (Shamsudduha and Uddin 2007). This river system forms the world's largest delta, the Ganges-Brahmaputra-Meghna (GBM) Delta that covers almost all of Bangladesh. The surficial geology (Fig. 2) is characterized by the Quaternary sedimentary deposits that are surrounded along basin margins by Precambrian metamorphic and igneous rocks to the west (Indian Shield) and near-north (Shillong Massif), fluvial Siwalik deposits to the far north (The Himalayas), and folded bedrocks of Tertiary age (Indo-Burman Mountains) to the northeast and southeast (Uddin and Lundberg 1998; Goodbred and Kuehl 2000). The Pleistocene terrace deposits (i.e., Madhupur and Barind Tracts), located in slightly elevated (10–20 m above sea level) central and northwestern parts of Bangladesh (Fig. 2), are generally brown or tan colored, highly weathered, and more compacted than floodplain and deltaic deposits that are generally young (Holocene age), gray colored, and composed of sand, silt, clay, and occasional peat deposits (UNDP 1982; BGS and DPHE 2001). Sediments in northeastern Sylhet depression and southern tidal-deltaic regions are predominantly silt and clay with little sand (Goodbred and Kuehl 2000). Spatial distributions and thickness of the upper silt and clay (USC) unit show (Fig. 2) that aquifers across the country are overlain by silt and clay sequences ranging from <5 to 50 m thick (MPO 1987). In northwestern regions (alluvial fan deposits), this USC unit does not exist where very fine to fine sands generally occur at the surface. However, shallow aquifers occur at relatively deeper (>15 m below ground level, bgl) depths in the Madhupur and Barind Tracts, Sylhet depression, and southern GBM Delta where the USC unit is thick.

The composition of soil in different surface geological units of Bangladesh varies as a function of proportions of sand, loam (silt), and clay—see electronic supplementary material (ESM Fig. SI). Average soil composition for individual soil classes was examined and later aggregated over a total of 30 agro-ecological zones in the country by Bangladesh Agricultural Research Council (BARC 1988). Soil composition in alluvial fans, major river valleys, and Tertiary deposits in eastern hilly terrains are predominantly sandy. In contrast, soil composition in Pleistocene terraces (Madhupur clay formation), tidal delta, and marshy peatland are mainly clayey. Surface geology and soil composition which generally characterize shallow aquifers in Bangladesh largely control the timing and pathways of groundwater recharge to aquifers (MPO 1987; WARPO 2000).

Groundwater in Bangladesh generally occurs at shallow (<10 mbgl) depth within widespread alluvial deposits (MPO 1987). Shallow groundwater levels essentially follow surface topography. Groundwater levels are higher in northwestern parts of the country but generally low in the south and within large topographic lows such as Sylhet and Atrai depressions (see ESM Fig. S2). Basin-scale elevation transects show the location (in ESM Fig. S3) of major river valleys and topographic lows serving as areas of regional groundwater discharge (e.g., Sylhet depression).

Several classification schemes have been proposed to distinguish aquifers in Bangladesh; "shallow" and "deep" are the two most popularly used terms found in literature but the location of the contact between these two and the basis of hydrologic separation are not well defined (Michael and Voss 2009). Aquifers that occur within the upper 80–100 mbgl of the stratigraphic sequence are generally identified as the shallow aquifer, and the deep aquifer occurs at >100 mbgl (Ravenscroft 2003). Deep aquifers provide municipal and industrial water supplies in urban areas and drinking-water supplies in coastal areas where shallow groundwater is mostly saline (UNDP 1982; BGS and DPHE 2001).

Groundwater-fed irrigation in Bangladesh

Agriculture in Bangladesh was entirely dependent on surface water and monsoon rainfall prior to the 1970s (UNDP 1982). Irrigated agriculture using groundwater through power-operated pumps was introduced in the 1970s to produce high-yielding ("Boro") rice in some parts of Bangladesh (MPO 1987). Boro rice grows during the dry season (December–April) when rainfall is low and episodic and typically requires 0.4–1.5 m of irrigation which is almost entirely groundwater-fed (Ravenscroft et al. 2009). Initially, a few irrigation wells were installed in northwestern parts of Bangladesh, but during the international campaign of "Clean Drinking Water Decade"

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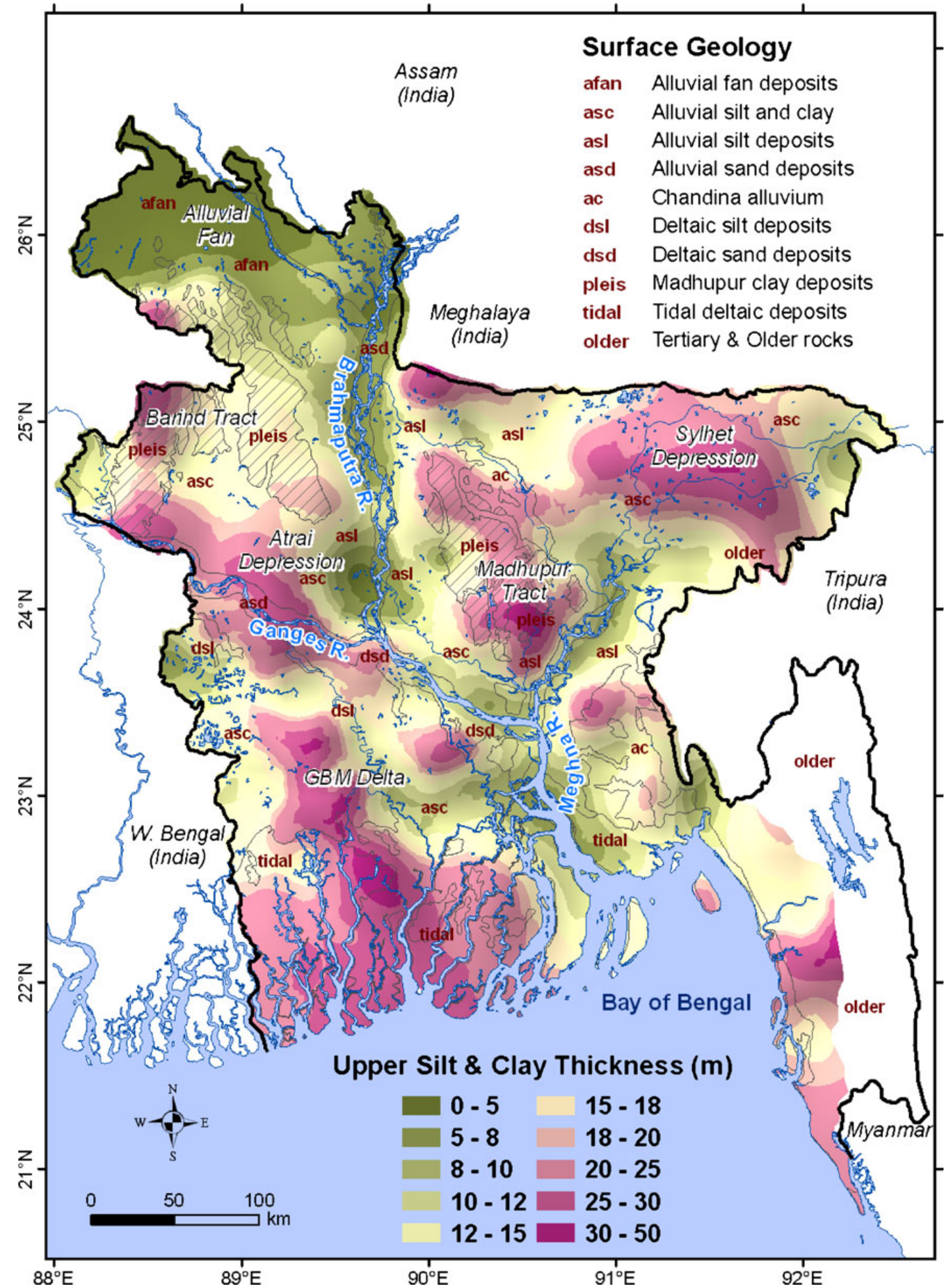

Fig. 2 Map of the thickness of the upper silt and clay (USC) unit in Bangladesh derived from borehole lithologs compiled by UNDP (1982), MPO (1987), and this study. Major surficial geological units are mapped highlighting (*hatch lines*) the location of thick clay-covered Madhupur and Barind Tracts (Pleistocene deposits). Note that data ranges for each class are discrete in that, for example, 0–5 m means 0 to <5 m

(1980–1990), the government and private sector installed millions of drinking water (hand tubewells, HTW) and shallow irrigation wells (WARPO 2000; BGS and DPHE 2001; World Bank 2005). By 2006, nearly 78% of the

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irrigated rice-fields were supplied by groundwater of which approximately 80% of the irrigation water derived from low-capacity (average discharge rate 10 L/s) shallow tubewells (STW; depth <80 mbgl); the rest was irrigated by high-capacity (average discharge rate 56 L/s) deep tubewells (DTW; depth >80 mbgl) to produce Boro rice (UNDP 1982; BBS 2009). Groundwater-fed irrigation (STW and DTW combined) is highest in northwestern and southwestern districts and lowest in eastern and southern deltaic regions in Bangladesh (Fig. 1) where surface-water irrigation is supplied mainly by low-lift pumps (LLP) and irrigation canals (BADC 2008). The total land area irrigated by DTWs and other surface-water based technologies remains relatively unchanged since the 1990s but the STW-based irrigation has linearly increased by two orders of magnitude over the last 30 years (Fig. 3).

To assess the impact of groundwater abstraction on recharge in Bangladesh, three different periods were defined, over which groundwater recharge is estimated. The first period (1975–1980) is the "pre-developed groundwater-fed irrigation (PGI)" which occurs prior to the onset of widespread groundwater-fed irrigation in the country. During the PGI period, shallow tubewell (STW) based irrigation covered an average area of 57,000 hectare (ha) and deep tubewell (DTW) covered an average area of 138,000 ha (Fig. 3). The second period (2002–2007) is the "developed groundwater-fed irrigation (DGI)" that occurs after widespread development of groundwater for irrigation in Bangladesh. During the DGI period, STW-based average irrigated area increased to 3,044,000 ha and DTW-supplied area increased to 702,000 ha. The third period (1985–2007) represents the long-term development phase of groundwater-fed irrigation (LGI) in Bangladesh.

Previous estimates of groundwater recharge in Bangladesh

There have been several efforts to estimate groundwater recharge to shallow aquifers in Bangladesh using different methods and datasets since the early 1970s. It is necessary to clarify terminology used in historical studies to define groundwater recharge. Actual (net) groundwater recharge is defined as the amount of water that infiltrates to the water table through subsoil and is primarily responsible for the net rise in annual groundwater levels. Potential recharge is defined as the total amount of water which could theoretically reach the water table. Rejected recharge is the fraction of water available at the surface but unable to infiltrate and percolate down to aquifers because the aquifer is fully saturated and the water table is at the ground surface. Usable recharge is the fraction (up to 75%) of potential recharge after accounting for uncertainties associated with the potential recharge due to poor model calibration, land use, and flood-control development. The "aquifer full" condition is achieved when the aquifer is fully replenished and potential recharge contributes to surface runoff (MPO 1987; Ravenscroft 2003).

The first study by the International Bank for Reconstruction and Development (IBRD 1972) estimated potential recharge from the difference between effective rainfall and potential evapotranspiration (ESM Fig. S4a). A more comprehensive study was later conducted by the United Nation Development Program (UNDP 1982) wherein potential recharge was defined as the excess amount of rainfall over the surface runoff and potential evapotranspiration (Fig. 4a). During the 1980s, the Bangladesh Water Development Board and UNDP (BWDB and UNDP 1983) provided a more sophisticated estimate of potential recharge (ESM Fig. S4b) for northwestern and north-central parts of the country using a water-balance method that considered both dry and wet percolation rates of aquifer units and variable recharge periods during the monsoon. Rates of groundwater recharge reported by BWDB and UNDP (1983) are much less than potential recharge since the rejected recharge was excluded from this estimate. Potential recharge, which mirrors annual rainfall, is higher in the eastern Bangladesh but such estimates can greatly exceed actual recharge (Ravenscroft 2003). Karim (1984) used borehole hydrographs to estimate actual groundwater recharge to shallow aquifers

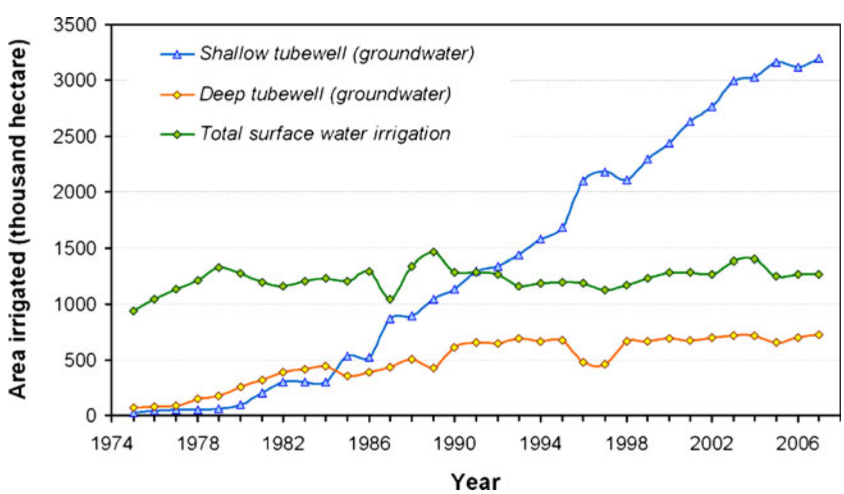

Fig. 3 Trends in annual records of the area irrigated by shallow tubewells, deep tubewells, and surface water in Bangladesh from 1975 to 2007

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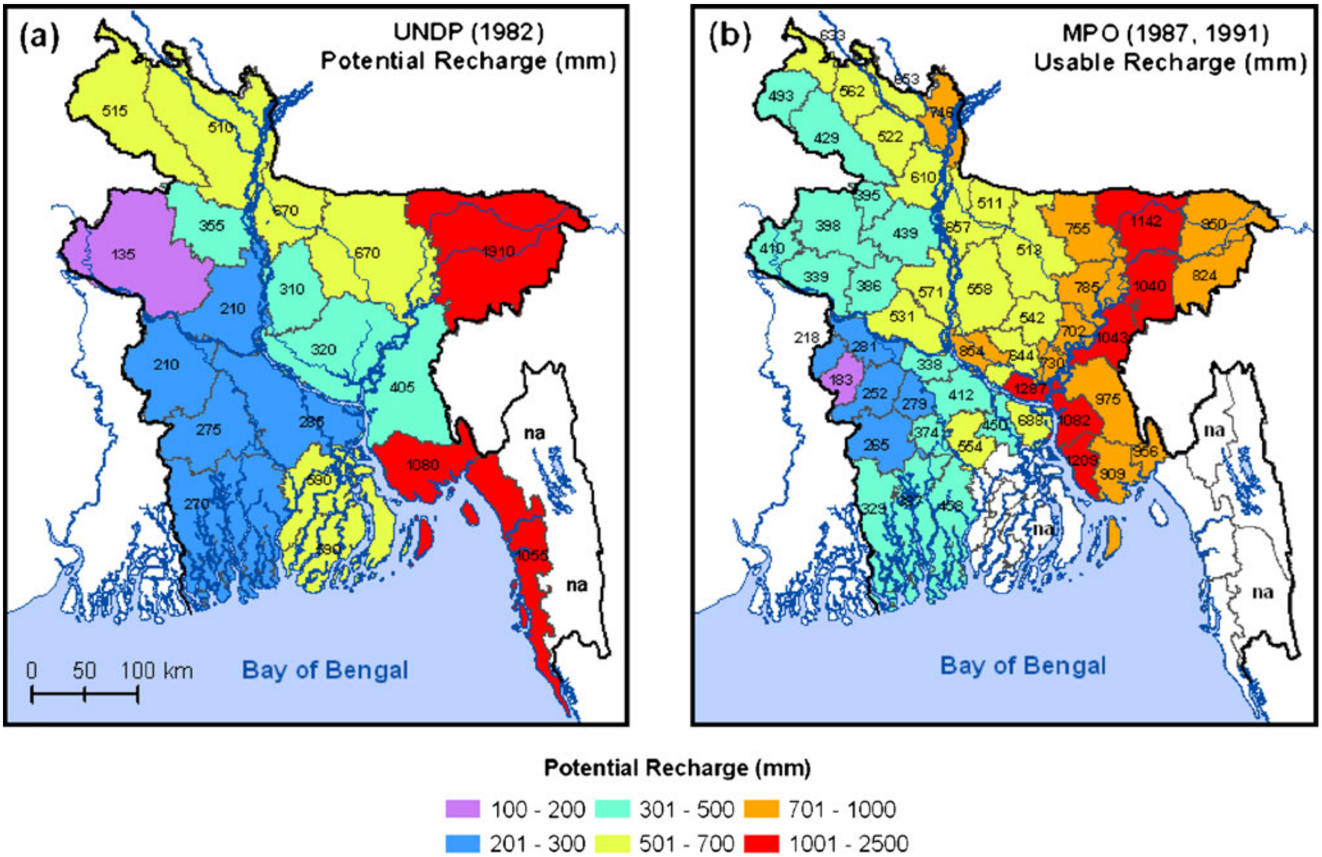

Fig. 4 National-scale potential groundwater recharge estimates by various studies: **a** estimates by UNDP, showing greater district-wise estimates of potential groundwater recharge (UNDP 1982); **b** estimates by MPO, showing district-wise usable/potential recharge (MPO 1987, 1991). *n.a.* means not available

between 1978 and 1983 (ESM Fig. S4c) and found recharge is lower in eastern Bangladesh compared to the western regions. Substantial uncertainty remains in these estimates due to the limited period of analysis and the use of tabulated specific yield values that are not reconciled to field conditions (Nishat et al. 2003). A more detailed analysis of potential and usable groundwater recharge (Fig. 4b and ESM Fig. S4d) at the nation-scale was conducted by the Master Plan Organization (MPO 1987, 1991) using finite-difference recharge models that considered a large number of physical, hydrological and agricultural parameters. These estimates indicate higher potential for groundwater recharge in Rivers Brahmaputra (Jamuna) and Meghna, and in eastern parts of Bangladesh.

Data sets and methods

Groundwater level database

Weekly measurements of groundwater levels in monitoring boreholes were used to estimate groundwater recharge to shallow aquifers. Shamsudduha et al. (2009a) compiled a national groundwater-level database (1.8 million weekly records) from a dense (one well per 105 km^2) network of 1,267 monitoring wells for the period of 1965–2007 operated by the Bangladesh Water Development Board. Currently, this network of groundwater-level monitoring wells has a total of 1,189 piezometers and 78 dug wells, mostly of shallow depths (<100 mbgl). A detailed description of the monitoring network as well as groundwater-level data processing and compilation procedure is given in Shamsudduha et al. (2009a). The mean depth of monitoring wells is approximately 30 mbgl with a standard deviation of 15 mbgl. These wells represent spatio-temporal groundwater dynamics of the shallow aquifer (<100 mbgl) in Bangladesh. Groundwater levels are referenced to a common datum (Public Works Datum, PWD) which was originally set to the mean sea level (msl) with a vertical error of ±0.45 m during the Great Trigonometric Survey in the Indian Subcontinent throughout the ninteenth century (Roy 1986).

Water-table fluctuation method

The water-table fluctuation (WTF) technique (Healy and Cook 2002) is applied to estimate net groundwater recharge. The principal assumption of the WTF method is that rises in the water level of an unconfined aquifer result from recharge arriving at the water table (Healy and Cook 2002). In Bangladesh, the overwhelming majority (>90%) of recharge to regionally unconfined (UNDP 1982) shallow aquifers occurs during the annual monsoon season (May–September; MPO 1987; WARPO 2000) though recharge can also take place during the dry season

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indirectly via ponds and return flow from irrigation (Harvey et al. 2006). The annual range in groundwater levels is used to estimate annual recharge at each monitoring location. The groundwater level time series is decomposed at each monitoring site into seasonal, trend and irregular components using a nonparametric seasonal-trend decomposition (STL) technique. The annual fluctuation in groundwater levels is represented by the seasonal component of the time series. A detailed description of the application of the STL technique to groundwater level data is given in Shamsudduha et al. (2009a). Specifically, the annual range of weekly-measured groundwater levels (Δh) between the maxima (during wet season) and minima (during dry season) is calculated at each location. This approach differs slightly from the typical WTF method where Δh is the difference between the peak water level and the theoretical lowest level which has been extrapolated along the antecedent recession curve to the time of the peak water level (see Fig. 1 in Healy and Cook 2002). Therefore, the minimum annual recharge estimate to the aquifer is derived. The calculation of net annual recharge for the PGI period (1975–1980) involves 177 monitoring wells of which there are 60 piezometers and 117 dug wells. The DGI period (2002–2007) involves 236 monitoring wells (borehole details are provided in ESM Table S1) which includes a total of 202 piezometers and 34 dug wells. Lastly, the estimate of recharge for the LGI period (1985–2007) (LGI) is used to derive trends in net recharge rates and involves the same monitoring wells as DGI period.

Recharge estimate for PGI period

Under natural or pre-developed groundwater-fed irrigation condition (PGI period) net groundwater recharge to aquifers can be estimated using Eq. (1) where R is net annual recharge, ΔS^{gw} is change in groundwater storage, Q^{bf} is baseflow to river channels, ET^{gw} is evapotranspiration from groundwater, and $Q^{gw}_{out} - Q^{gw}_{in}$ is the net groundwater flow from the study area.

$$R = \Delta S^{gw} + Q^{bf} + ET^{gw} + \left(Q^{gw}_{out} - Q^{gw}_{in}\right) \quad (1)$$

ΔS^{gw}, estimated using the WTF method over long time intervals (seasonal or annual), is sometimes referred to as "net" recharge (Healy and Cook 2002). In Bangladesh, Q^{bf} is inhibited during the monsoon period when river stages are universally higher than the water table (see ESM Figs. S2 and S5 for five hydrographs of groundwater and surface-water levels selected from a total of 43 paired stations analyzed in this study) and the shallow aquifer adjacent to major rivers experiences induced recharge through bank infiltration. Baseflow is restricted to the early part of the dry season (i.e., descending limb of the groundwater hydrograph) which does not affect annual water-table rises. ET^{gw} is assumed to be negligible throughout Bangladesh where land cover is dominated (>80%) by crops (e.g., rice paddy) with shallow <2 m rooting depths (Mishra et al. 1997) (see ESM Fig. S6) and dry-season water tables are >2 mbgl (see ESM Fig. S7). During the monsoon (ascending limb of groundwater hydrograph) soil moisture sustaining ET is predominantly supplied by rainfall and flood water, and ET^{gw} via capillary flow is inhibited by direct and indirect recharge fluxes to aquifers. The magnitude of ET^{gw} via capillary flow during the dry season is unclear. Net groundwater flow $\left(Q^{gw}_{out} - Q^{gw}_{in}\right)$ during the monsoon period is assumed to be negligible throughout the study area due to the absence of substantial hydraulic gradients in the water table of the shallow aquifer (Harvey et al. 2006; Shamsudduha et al. 2009b). Additionally, net groundwater flow $\left(Q^{gw}_{out} - Q^{gw}_{in}\right)$ from the shallow system through the submarine groundwater discharge is negligible since groundwater flux to the Bay of Bengal is likely to be controlled by the deep flow system that is driven by regional head gradients (Michael and Voss 2009). Equation (1) can, therefore, be simplified for the PGI period to Eq. (2) where S_y is specific yield, Δh is water-table height between annual maxima and minima, and Δt is time period (a year).

$$R = \Delta S^{gw} = S_y \partial h / \partial t = S_y \Delta h / \Delta t \quad (2)$$

Equation (2) is used to estimate annual net groundwater recharge at each monitoring well location (n=177) for the PGI period.

Recharge estimate for DGI and LGI periods

Groundwater abstraction can both amplify (Fig. 5a–b) and suppress (Fig. 5c) seasonal fluctuations in groundwater levels. For the former, pumping increases available storage in the aquifer over time (Fig. 6). Net recharge increases due to this rise in available storage and the capture of potential recharge that was previously rejected due to limited available storage. For the DGI period, actual recharge estimated via Eq. (2) includes both natural and abstraction-induced recharge ($R_{actual} = R_{natural} + R_{induced}$). Where groundwater abstraction is perennial (e.g., public water supplies in Dhaka City) and the capture of potential recharge is inhibited by low-permeability of surficial deposits (e.g., Madhupur and Barind Tracts), seasonality in groundwater fluctuation is suppressed (Fig. 5c) by the long-term trend associated with intensive abstraction. The annual groundwater fluctuation no longer effectively represents the total recharge fluxes and estimation of recharge requires the additional inclusion of abstracted groundwater. Net groundwater recharge in this case is estimated with Eq. (3) where Q^{p} is annual groundwater abstraction.

$$R = Q^{p} + \Delta S^{gw} \quad (3)$$

The suppression of seasonality in the groundwater-level time series is observed at four locations (see hydrographs in ESM Fig. S8) which include Dhaka City and a part of the Barind Tract. These locations were distinguished from the rest of the monitoring sites based on the following criteria: (1) seasonality in groundwater hydrograph represents <30% of the total variance in the

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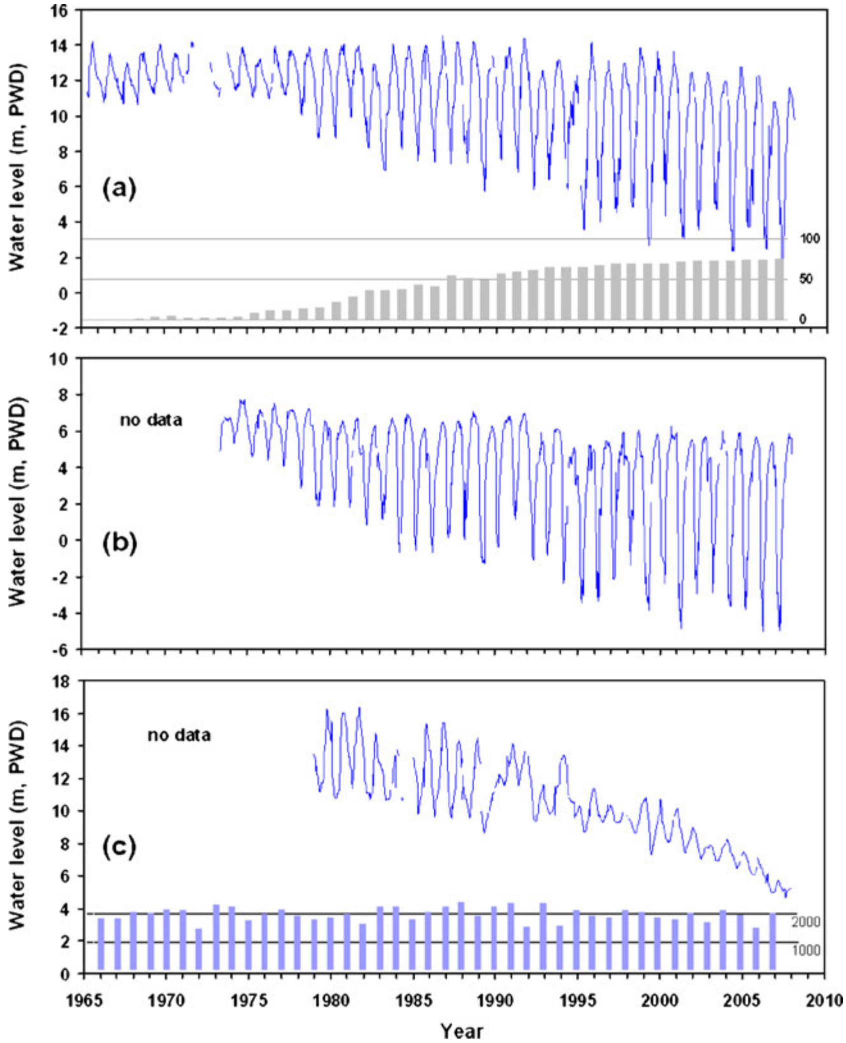

Fig. 5 Borehole hydrographs showing long-term changes in groundwater levels in areas of intensive groundwater-fed irrigation under different geological conditions: **a** shows the hydrograph of a dug well (RJ023_A) located in the alluvial silt and clay (ASC) geological unit where the upper silt and clay (USC) unit is thin (<10 m); **b** shows groundwater levels in a piezometer (CM004_A) of shallow depth (20 mbgl) where surface geology is permeable alluvial silt (asl) where thickness of the USC unit ranges from 10 to 15 m; and **c** shows rapidly declining trend and reduced seasonality in groundwater levels in RJ086_AB. Surface geology at this location is the Barind residuum (rb) of low vertical permeability and thickness of the USC unit is approximately 18 m. Percentage of areas in Bangladesh irrigated with groundwater is shown (**a**); mean annual rainfall (mm) from 1965 to 2007 is depicted (**c**)

time-series (Shamsudduha et al. 2009a), and (2) groundwater abstraction is intensive. Recent studies (Hoque et al. 2007; Shamsudduha et al. 2009a) report that increased abstraction for urban and irrigation water supplies in Dhaka City and Barind Tract region draws groundwater from storage. Q^{p} was estimated in Dhaka City using abstraction data recorded at a total of 421 boreholes managed by Dhaka Water Supply and Sewerage Authority (DWASA; Hoque et al. 2007; Akther et al. 2009). In addition to DWASA wells, there are approximately 1,000 private boreholes where no systematic monitoring exists. Q^{p} in Barind Tract was estimated for the period of 2002–2007 using irrigated area (BADC 2008) and water requirements for rice and non-rice plants (MPO 1987; Ravenscroft 2003).

Net groundwater recharge at each of the monitoring locations was estimated using a programming routine in R language (R Development Core Team 2007) and interpolated at the national-scale using the geostatistical kriging technique on ESRI ArcGIS (v.9.2) with a modeled semivariogram to generate the contoured map.

Specific yield of shallow aquifers

Specific yield (S_y) is a measure of the release of groundwater from storage in an unconfined aquifer as the water table drops during an event of abstraction or natural discharge (WARPO 2000). Specific yield values at sites of groundwater-level monitoring were derived from pumping tests conducted at 279 locations by the Ground Water Circle of Bangladesh Water Development Board between 1972 and 1992 as part of the national groundwater survey and investigations (UNDP 1982; BWDB 1989, 1994). The majority of these pumping tests were performed

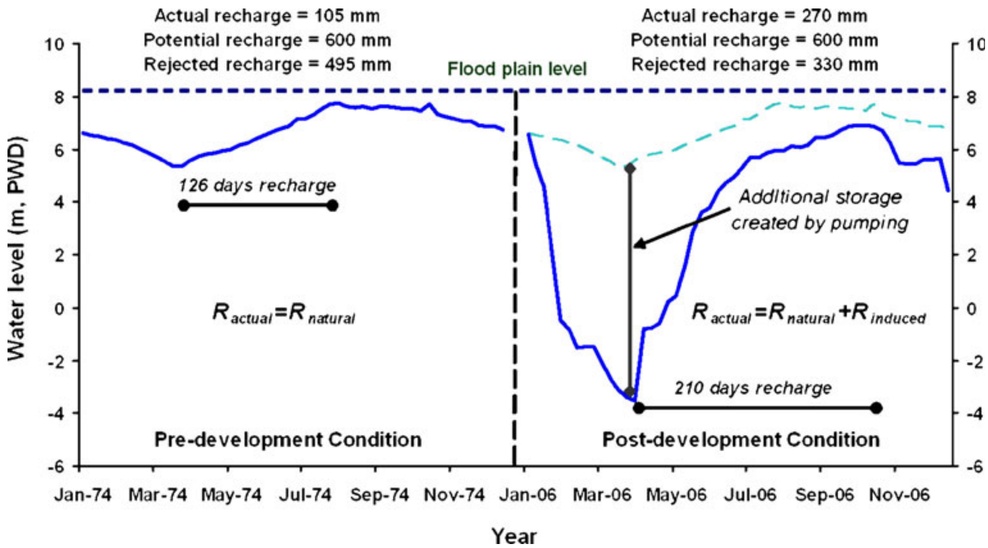

Fig. 6 Hydrograph shows increase in groundwater recharge due to rise in available storage created by long-term abstraction for groundwater-fed irrigation. The monitoring well (CM004_A) is located in Burichang Thana of Comilla district in eastern Bangladesh where 82% cultivable lands are under groundwater-fed irrigation schemes. Recently, increase in available storage captures potential recharge that was previously rejected due to "aquifer full" condition. The aquifer in this location takes about 7 months to recharge following a water-table drop to its deepest level during the dry-season irrigation

between 1976 and 1985 in a total of 188 monitoring locations. Hydraulic testing occurred during a period when groundwater-fed irrigation was not fully developed in most parts of the country (BWDB 1989). These tests derived different hydraulic parameters of shallow aquifers including transmissivity (T), hydraulic conductivity (K), and specific yield (S_y) or storativity in alluvial aquifers. Pumping tests were primarily conducted in Bangladesh Agricultural Development Corporation (BADC) irrigation wells and newly installed boreholes ranging in depth from 50 to 100 mbgl. Pumping tests reported that the alluvial aquifer system in most parts of Bangladesh is primarily composed of a number of stratified and unconfined aquifers with greater transmissivity (mean 1,270±770 m^2/day) and specific yield ranging from 0.01 to 0.20 (ESM Fig. S9) with a national average of 0.06±0.04 (UNDP 1982; BWDB 1994).

The geographic locations of pumping-test wells and BWDB groundwater-level monitoring wells are not the same. The spatial join function in the ESRI ArcGIS (v.9.2) environment is used with a set of selection criteria to extract specific yield values at each of the 236 well locations. Specific yield values from the national pumping-test database were chosen for each groundwater-level well following two conditions: (1) each pair of wells are located in the same geological unit; and (2) maximum distance between the pumping-test well and groundwater-level well in each pair is <50 km. Extracted data sets of pair of wells show that the mean distance between each pair of groundwater-level and pumping-test wells is <10 km and wells are located in the same geological unit. Derived specific yield values at 236 locations show a mean value of 0.06 with a standard deviation of 0.03.

Pumping-test derived specific yield values represent well the stratigraphy of shallow aquifers from the upper 20 m down to a depth of 90 mbgl. Groundwater fluctuations in most monitoring wells often occur within a depth of 10 mbgl. To include a depth-variable S_y value, specific to the zone of water-table fluctuations (0–10 mbgl) within the upper part of the aquifer, another set of S_y data is applied derived from borehole lithological records throughout Bangladesh (MPO 1987). At the national-scale S_y values derived from both pumping tests (ESM Fig. S9a) and borehole lithology (ESM Fig. S9b) show a similar pattern with the highest values concentrating in alluvial fans and Brahmaputra River valley and the lowest in southern parts of the GBM Delta and most of Sylhet depression as well as Madhupur and Barind Tracts. When estimating groundwater recharge at each monitoring site, a programming routine in "R" environment (R Development Core Team 2007) is used which allows every well to choose depth-specific S_y values depending on the occurrence of groundwater fluctuation in the stratigraphic column. For example, some groundwater-level monitoring wells in the flat Barind region, where thickness of the upper silt and clay (USC) unit is <10 m, show abrupt changes in the mean water-table depth between two consecutive years. In these wells, the mean water-table level occurred within the USC zone for most of the 1990s but recently dropped below the clay layer and water level now occurs in the aquifer sand unit where S_y is almost an order magnitude higher than that of the overlying aquitard (WARPO 2000). The approach used here, of using depth-variable S_y values, is able to consider such abrupt but significant variation in aquifer storage capacity to provide reasonable estimates of net groundwater recharge.

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Results

Groundwater recharge estimates

Estimates of groundwater recharge are shown in Fig. 7 for three time periods: (1) pre-developed groundwater-fed irrigation (PGI) period (1975–1980), (2) post-developed groundwater-fed irrigation (DGI) period (2002–2007), and (3) long-term mean recharge (LGI) period (1985–2007). The results show that actual (net) recharge is higher in northwestern (Dinajpur district) and western parts (Rajshahi district) of Bangladesh than in southern (Khulna district) and eastern parts except for Comilla district (Fig. 7). The magnitude of groundwater recharge varies substantially between the PGI and DGI periods. Greater increases in the net recharge are observed in northwestern regions and along the Rivers Brahmaputra and Ganges; changes in recharge are limited in the rest of the country. The net recharge also increased recently in Jessore (north of Khulna district), Mymensingh and Comilla regions. Recent mean annual recharge (2002–2007) is greater than the long-term (1985 to 2007) mean recharge in some parts of the northwestern Bangladesh and in the River Brahmaputra floodplains.

Spatio-temporal trends in groundwater recharge

Figure 8 shows changes in actual groundwater recharge for the period of 1985–2007. Recharge has increased substantially (5–15 mm/year) in northwestern and western districts (Bogra, Dinajpur, Gaibandha, Jessore, Jhenaidah, Rangpur, and Rajshahi), north-central districts (Dhaka, Jamalpur, Mymensingh, Tangail districts), and Comilla district in the east, but has slightly decreased (−0.5 to −1 mm/year) or remained unchanged in the rest of Bangladesh (Fig. 8a). Decreases in the net groundwater recharge are observed in southern GBM Delta and Sylhet depression. Spatial variations in changes to net annual recharge (absolute difference) between the PGI and DGI periods are shown in Fig. 8b at the national scale. Annual recharge in many places has increased by 100–350 mm between these two observation periods. A reduction in the net groundwater recharge (10–50 mm) is observed mainly in the tidal GBM Delta and some parts of northeastern region in Bangladesh. Greatest increases in net groundwater recharge between the PGI and DGI periods coincide with areas of intensive groundwater-fed irrigation indicated by graduated circles in Fig. 8b.

Discussion

Relationship between actual (net) and potential groundwater recharge

Increases in groundwater recharge may be possible where actual (net) recharge is less than potential recharge estimated previously (section Previous estimates of groundwater recharge in Bangladesh). The estimates of net recharge in northwestern and western parts of Bangladesh are much greater than in eastern parts where potential recharge is higher due to greater annual rainfall (>2,000 mm). Net annual recharge in western parts of the country has substantially increased since the 1980s and now approximates potential recharge. Net recharge is high (300–600 mm) along the Rivers Brahmaputra and Ganges where potential recharge was previously estimated to be 500–700 mm (MPO 1987, 1991). Net recharge in northwestern parts of the GBM Delta ranges from 250 to 600 mm and similarly approximates potential recharge. In southeastern GBM Delta and Sylhet regions where estimated potential recharge is high (400–2,000 mm; UNDP 1982; MPO 1987, 1991), the net annual recharge is considerably lower (<150 mm). The substantial difference between actual and potential recharge in these areas suggests that a major fraction of the available recharge is lost through surface runoff and evapotranspiration. The United Nation Development Programme (UNDP 1982) calculated potential recharge using a hydrological balance where runoff was estimated to be 20–40% of the annual precipitation. However, annual runoff in northeastern parts of Bangladesh (Sylhet) can be as high as ~3,000 mm (75% of annual rainfall; Fekete et al. (1999). Therefore, much of the monsoon rainfall is converted to surface runoff and routinely generates floods in low-lying areas (WARPO 2000). Net annual recharge in coastal areas is also much lower than potential recharge. Shallow water tables in southeastern GBM Delta, and floodplains of Rivers Meghna and Brahmaputra reach peak levels during the early (July–August) part of the monsoon season (see ESM Fig. S10) indicating that aquifers are fully recharged. In contrast, shallow aquifers in the north-central and western parts of the country experience longer period of recharge following a substantial drawdown during the dry-season groundwater-fed irrigation.

Fig. 7 Map of estimated actual (net) groundwater recharge to shallow aquifers in Bangladesh using the water-table fluctuation method for three time periods: **a** mean annual recharge for a 6-year period of 1975–1980 related to the pre-developed or underdeveloped groundwater-fed irrigation period in Bangladesh, **b** mean recharge for the period of 2002–2007 showing higher recharge in fully-developed irrigation era, **c** mean annual recharge over a period of 23 years (1985–2007) in Bangladesh

Impacts of groundwater abstraction on recharge

Net groundwater recharge has increased in many areas of Bangladesh since the 1980s where intensive dry-season irrigation sustains Boro rice cultivation. Previous groundwater studies in Bangladesh (UNDP 1982; MPO 1987, 1991; WARPO 2000) suggest that greater groundwater-fed irrigation will increase net recharge in areas where surface geology and soil properties are permeable and thereby favor recharge. Numerical modeling of regional groundwater flow suggests that actual (net) recharge increased from around 70 mm/year prior to widespread groundwater-fed irrigation (before 1970s) to around 250 mm/year more recently (Michael and Voss 2009). The estimates of net recharge (Fig. 8b) show that mean recharge in Bangladesh has increased from 132 mm/year

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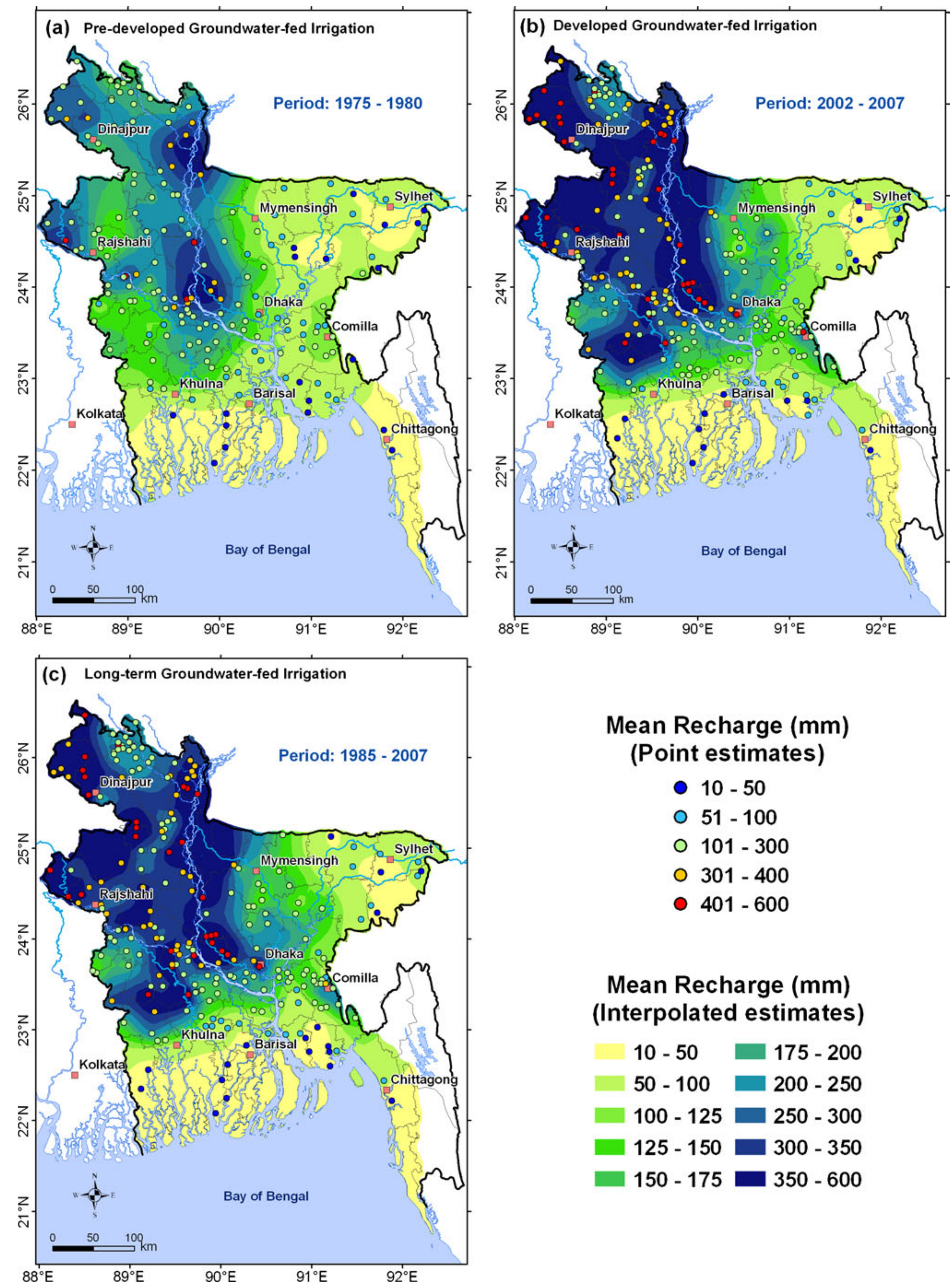

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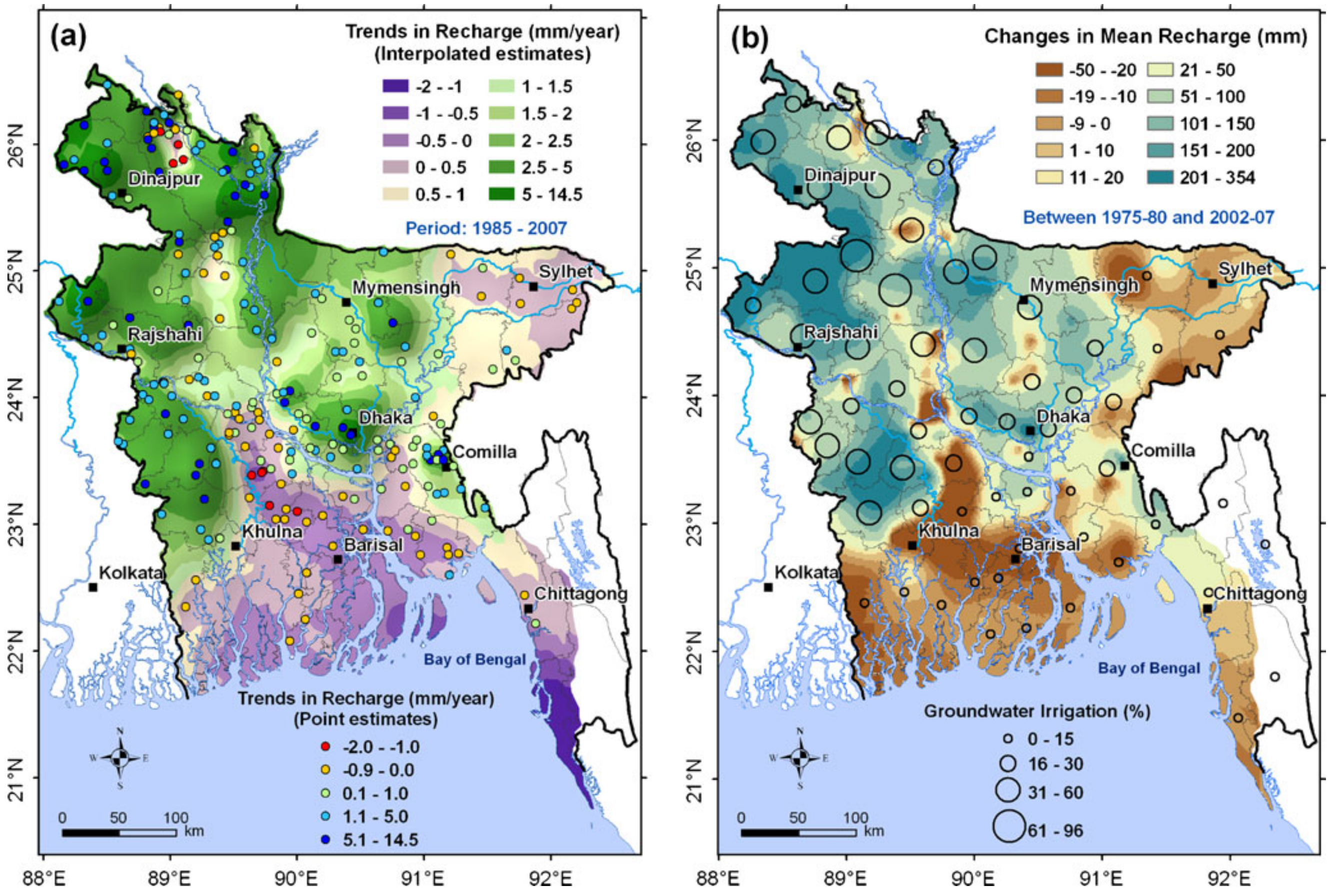

Fig. 8 Spatio-temporal changes in the net groundwater recharge across the shallow aquifer in Bangladesh in terms of **a** long-term trends in groundwater recharge between 1985 and 2007 and **b** absolute changes (mm) in net recharge between two periods, 1975–1980 and 2002–2007. Percentage of groundwater-fed irrigated areas (2005–2006) in each of the country's 64 districts is shown as *graduated circles*. Areas with higher groundwater-fed irrigation experience greater rise in actual recharge with time

over a period from 1975 to 1980 to approximately 190 mm/year for the period 2002–2007.

Net groundwater recharge can rise if greater dry-season abstraction increases the available aquifer storage capacity where a large (positive) difference exists between actual and potential recharge. In Bangladesh, the proportion of arable land irrigated by groundwater increased from <1% in 1965 to approximately 78% in 2007 (Fig. 5a). Recharge has increased in areas (hydrographs shown in Fig. 5a and b) where dry-season groundwater levels have declined 5–10 m since the pre-irrigation period but where wet-season water levels have remained more or less unchanged over the period of observation. This steady rise in net recharge has occurred without any increasing trend in annual rainfall (Fig. 5c). Available groundwater storage has increased to accommodate greater recharge that previously had been rejected during the pre-irrigation period after reaching the "aquifer full" condition. For example, net recharge at the monitoring well RJ023_A (Fig. 5a) in Mohanpur Thana (A "Thana" is the third-level administrative unit in Bangladesh) of Rajshahi district increased from 125 mm in 1965 to approximately 430 mm in 2007 where potential recharge is estimated to be 450 mm (MPO 1991). Although net groundwater recharge increased substantially at this location, a steady decline in wet-season groundwater levels suggests recent depletion in storage. The borehole hydrograph for monitoring well CM004_A (Comilla district) indicates that net recharge has recently increased to 270 mm from 105 mm during the PGI period (Figs. 5b and 6); potential recharge is estimated to be approximately 600 mm (MPO 1987).

Increases in actual groundwater recharge are limited in areas of intensive abstraction where direct rain-fed recharge is inhibited by low-permeable surface geology and net recharge is approaching or has reached potential recharge. At monitoring well RJ086_AB (Fig. 5c) in the higher Barind Tract (low-permeable geology), net groundwater recharge has only marginally increased (200 to 230 mm from PGI to DGI periods) yet groundwater-fed irrigation in this area (Tanore Thana) has increased from <50 to 375 mm over the period of 1985–2007.

Reductions in net groundwater recharge are observed in several areas of Bangladesh including Sylhet depression, lower Ganges floodplains, and tidal deltaic areas (Fig. 8). Abstraction for groundwater-fed irrigation in these areas is lower (<30%) than the rest of Bangladesh. Groundwater-fed irrigation has slightly decreased (−0.5 to −1 mm/year between 1985 and 2007) in some areas in Sylhet and coastal regions. Recently, many agricultural lands (rice fields) in the

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coastal areas of the country have been transformed into brackish-water shrimp farms (Ahmed et al. 2009). Actual recharge to shallow aquifers in these areas has declined, in part, from a reduction in groundwater abstraction for dry-season irrigation.

Indirect recharge: interactions between groundwater and surface water

Net groundwater recharge along the Rivers Brahmaputra (Jamuna) and Ganges (Padma; 350–600 mm) is much higher than that in the River Meghna and the GBM Delta (<150 mm). Sediments in floodplains of the River Brahmaputra are generally sandy and the storage capacity of adjacent aquifers is higher than the deltaic plains. In addition to a high specific yield, the transmissivity of shallow aquifers in the Brahmaputra floodplains are greater (3,500–7,000 m^2/day) than those in Ganges and Meghna floodplains (3,000–5,000 m^2/day), and terrace and deltaic aquifers (300–3,000 m^2/day) in Bangladesh (UNDP 1982; BGS and DPHE 2001). Interactions between groundwater levels and water levels in the River Brahmaputra are highly dynamic showing similar magnitudes (6–8 m) of annual fluctuation between dry and wet seasons. Analysis of groundwater level and river-stage hydrographs (see ESM Figs. S2 and S5) reveals that water levels in almost all river channels rise above groundwater levels in adjacent aquifers during the monsoon season (May–September); indirect recharge is restricted to lateral river-bank infiltration during the early monsoon time (April–June). Shallow aquifers adjacent to the River Brahmaputra mostly experience greater indirect groundwater recharge. Water levels in the River Brahmaputra generally rise earlier (March–April) than those of the Rivers Ganges and Meghna due to increased fluxes from snowmelt water in the Himalayas (WARPO 2000). Additionally, stable isotope (^{18}O and ^{2}H) data and geochemical analyses of river and groundwater compositions suggest close interactions between the River Brahmaputra and adjacent shallow aquifers whereas indirect recharge from the River Ganges is much lower (MPO 1987). Aquifers adjacent to the River Meghna receive the least indirect groundwater recharge as hydrographs shows that water levels both in the shallow aquifers and river-channel respond coincidently to the monsoon pulse (see ESM Fig. S5c). Baseflow discharges from groundwater to upper reaches of the River Surma-Meghna during the dry season are negligible (see river discharge hydrographs in ESM Figs. S11 and S12). Additionally, in lower reaches of the River Meghna at Bhairab Bazar station (near the confluence with the River Old Brahmaputra) dry-season discharge is also extremely low similarly suggesting negligible baseflow from groundwater (WMO and GWP 2003).

Constraints of groundwater recharge: further development

The national-scale analysis of net groundwater recharge in Bangladesh, reported here, shows areas where recharge to shallow aquifers has generally increased following widespread groundwater abstraction for irrigation and urban water supplies. Net recharge to aquifers in western and southwestern parts of the country is nearly equal to potential recharge. Potential recharge is, however, much greater than the current rates of net recharge in eastern and southern parts of the country where annual rainfall is high (>2,500 mm/year). Further increases in groundwater abstraction in western and southwestern parts of Bangladesh may further lower dry-season groundwater levels but not increase net recharge because the current recharge rate has reached estimated potential recharge.

In Bangladesh, shallow aquifers can reach the “aquifer full” condition by monsoon recharge but greater abstraction in many places can reduce dry-season groundwater levels so that irrigation is no longer possible by low-cost pumping technologies (Fig. 9a). For instance, dry-season groundwater levels in many areas have recently dropped below 15 mbgl which prevents abstraction of groundwater by hand pumps and peristaltic pumps. Figure 9 shows areas where (Comilla, Dhaka, Gazipur, Mymensingh, Nawabganj, and Rajshahi districts) dry-season groundwater abstraction is restricted to more expensive, high-capacity pumps (e.g., submersible, vertical turbine, and super Tara pumps).

Groundwater abstraction and “safe yield” of aquifer

The national-scale analysis of groundwater recharge provides a clear quantitative illustration of the fallacy of the concept of “safe yield”. Previous criticisms of this concept (e.g., Sophocleous 2000; Alley and Leake 2004; Zhou 2009) have been based solely on theoretical arguments. In this study, direct evidence is presented of regional changes in net recharge in response to abstraction. The assertion that the sustainability of groundwater abstraction is based on long-term average recharge (e.g., Döll and Fiedler 2008; Kundzewicz and Döll 2009; Döll 2009) fails to recognize the critical influence of abstraction on recharge rates. The analysis reported here also highlights the necessity of reconciling recharge estimates to local geology and soil permeability as these properties play a fundamental role in determining recharge. To sustain groundwater development, it is critical to distinguish areas (such as Bogra, Brahmanbaria, Chandpur, Comilla, Gaibandha, Kishoreganj, Manikganj, Munshiganj, Rangpur, Sirajganj and Tangail districts; Fig. 9b) where further abstraction may induce greater recharge (i.e., soils and geology are favorable and potential recharge is much greater than current recharge rates) from areas (such as Chuadanga, Dhaka, Gazipur, Jaypurhat, Jessore, Jhenaidah, Kushtia, Magura, Naogaon, Natore and Rajshahi districts; Fig. 9b) where it will not.

Conclusions

Groundwater recharge has increased substantially in north-central, northwestern, and parts of southwestern Bangladesh following the widespread adoption of ground-

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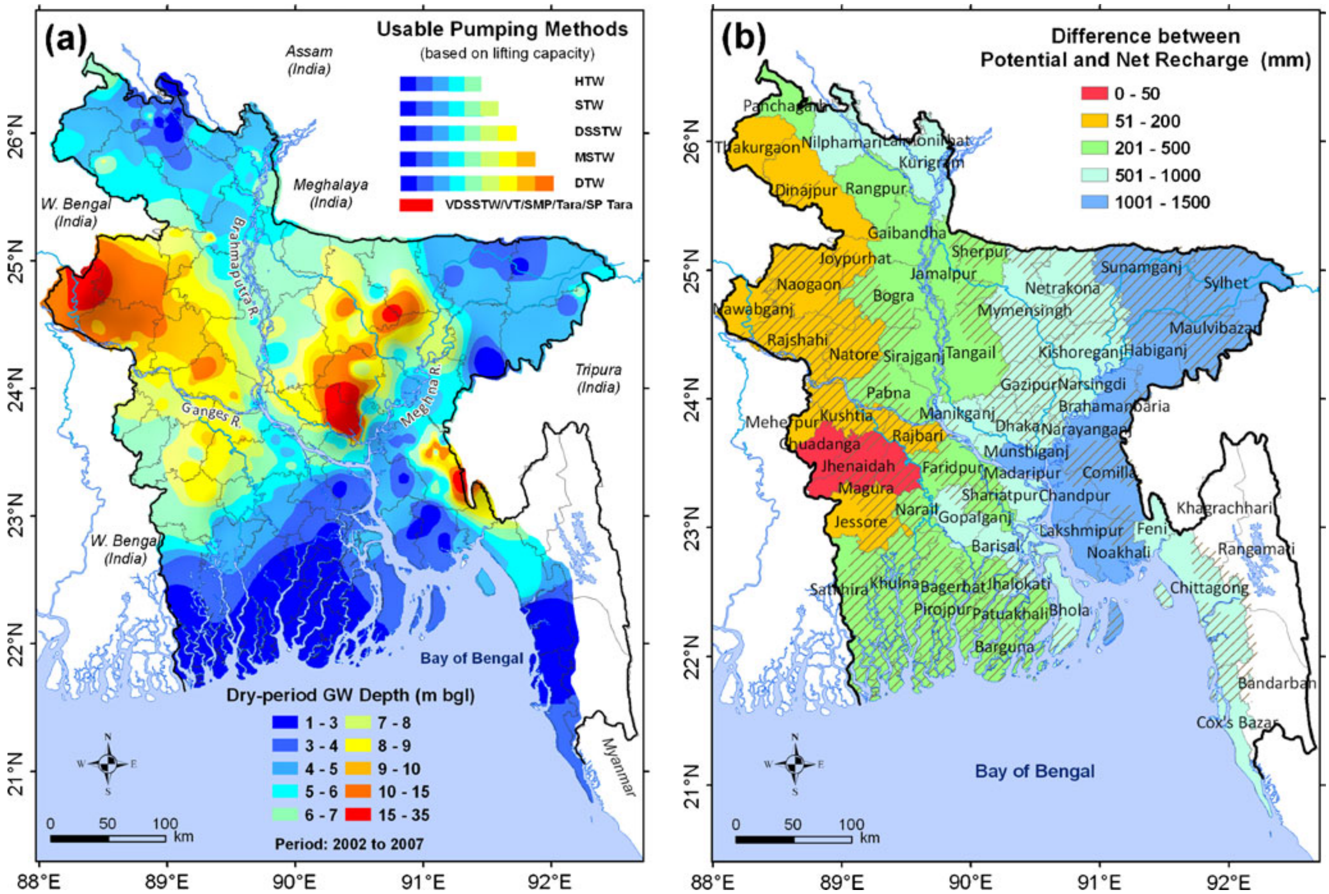

Fig. 9 **a** Map shows the maximum depth (mbgl) to the recent (2002–2007) static water table in aquifers in Bangladesh. This map highlights the areas where currently available pumping technologies for drinking water and irrigation water supplies are unusable during the dry season. *HTW* hand tubewell, *STW* shallow tubewell, *DSSTW* deep set shallow tubewell, *MSTW* mini-submersible shallow tubewell, *DTW* deep tubewell, *VDSSTW* very deep-set shallow tubewell, *VT* vertical turbine pump, *SMP* submersible pump, *Tara* Tara pump, *SP Tara* super Tara pump; **b** Map shows part of the potential recharge available for further groundwater development in 64 districts in Bangladesh. Further increase in net recharge due to increased abstraction in the western parts of Bangladesh is constrained by the limited quantity of potential recharge and surface geology. *Hatch lines* show areas where the thickness of the upper silt and clay unit is >15 m

water-fed irrigation for dry-season Boro rice cultivation in the 1980s. Groundwater-fed irrigation lowers the water table in shallow aquifers during the dry season which induces greater recharge by increasing available groundwater storage during the subsequent monsoon. It is shown that the greatest increases in groundwater recharge have occurred where the density of groundwater-fed irrigation is highest. Anomalous reductions (−0.5 to −1 mm/year between 1985 and 2007) in groundwater recharge have taken place in areas of low groundwater abstraction for irrigation. The national-scale distribution of actual (net) groundwater recharge differs substantially from estimates of potential recharge reported by previous studies which show greater potential recharge in eastern Bangladesh where rainfall is highest. These national-scale dynamics of groundwater recharge in Bangladesh highlight three fundamental points regarding the relationship between groundwater recharge and abstraction: (1) rates of groundwater recharge can change substantially (5–15 mm/year; 1985–2007) in response to abstraction; (2) estimates of potential recharge can greatly exceed actual groundwater recharge; and (3) the magnitude of the difference between potential and actual recharge provides a measure of possible increases in groundwater recharge that may be realized through greater groundwater abstraction. The first observation illustrates well the fundamental flaw in definitions of "safe yield" based on estimates of groundwater recharge under static (non-pumping) conditions. The second shows how values of (potential) recharge derived from current macro-scale hydrological and land-surface models, unreconciled to the transmissivity and storage of the underlying soils and geology, can substantially overestimate net groundwater recharge fluxes. The third enables areas where further abstraction may induce greater groundwater recharge to be distinguished from areas where increases in net recharge are limited and any further rises in abstraction may deplete groundwater storage and lower the water table (i.e., actual recharge is nearly equal to potential recharge). Falling water tables in some areas of Bangladesh (Rajshahi, Jessore and Dhaka districts) have already restricted access to groundwater via shallow irrigation and hand-operated tubewells for food

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production and drinking-water supplies. Water-use policies should, therefore, recognize the dynamic nature of groundwater recharge and consider the spatio-temporal changes in water levels and abstraction to promote the sustainable use of groundwater resources in Bangladesh.

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